Received 1999 June 16; accepted 1999 July 7
Preprint typeset using LaTeX style emulateapj v. 04/03/99

HST OBSERVATIONS OF THE SERENDIPITOUS X-RAY COMPANION TO Mrk 273: CLUSTER AT z = 0.46?[a]

[a]BASED ON OBSERVATIONS WITH THE NASA/ESA HUBBLE SPACE TELESCOPE, OBTAINED AT THE SPACE TELESCOPE SCIENCE INSTITUTE, WHICH IS OPERATED BY THE ASSOCIATION OF UNIVERSITIES FOR RESEARCH IN ASTRONOMY, INC. UNDER NASA CONTRACT NO. NAS5-26555.

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Received 1999 June 16; accepted 1999 July 7

ABSTRACT

We have used HST *I*-band images to identify Mrk 273X, the very unusual high-redshift X-ray-luminous Seyfert 2 galaxy found by ROSAT in the same field-of-view as Mrk 273. We have measured the photometric properties of Mrk 273X and have also analyzed the luminosity distribution of the faint galaxy population seen in the HST image. The luminosity of the galaxy and the properties of the surrounding environment suggest that Mrk 273X is the brightest galaxy in a relatively poor cluster at $z \approx 0.46$. Its off-center location in the cluster and the presence of other galaxy groupings in the HST image may indicate that this is a dynamically young cluster on the verge of merging with its neighboring clusters. We find that Mrk 273X is a bright featureless elliptical galaxy with no evidence for a disk. It follows the de Vaucouleurs ($r^{1/4}$) surface brightness law very well over a range of 8 magnitudes. Though the surface brightness profile does not appear to be dominated by the AGN, the galaxy has very blue colors that do appear to be produced by the AGN. Mrk 273X is most similar to the IC 5063 class of active galaxies — a hybrid Sy 2 / powerful radio galaxy.

Subject headings: galaxies: active — galaxies: clusters: general — galaxies: individual (Markarian 273) — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

Mrk 273 (IRAS 13428+5608) is one of the nearest members (at z=0.0378) of a special class of galaxies — the ultraluminous infrared galaxies (ULIRGs) — identified by IRAS (Sanders *et al.* 1988a,b). It shows a long tidal tail and a disturbed morphology, thus indicating its presumed galaxy-galaxy collision+merger origin. The merger and its accompanying starburst and/or AGN activity leads to the high IR luminosity ($> 10^{12} L_{\odot}$) through dust absorption and re-emission of the intense but obscured radiation field. Mrk 273 has a Sy 2 nuclear spectrum (Lutz, Veilleux, & Genzel 1999) and consequently is a soft X-ray source (Turner *et al.* 1993). ROSAT PSPC X-ray observations of the field surrounding this galaxy and several other Sy 2 galaxies revealed the presence of serendipitous companion X-ray sources around each primary source (Turner *et al.* 1993; see also Laurikainen & Salo 1995, Radecke 1997, Arp 1997). The X-ray companion to Mrk 273 (hereafter, Mrk 273X) is 1.3′ to the northeast (projected separation $\approx$ 57 kpc, at the redshift of Mrk 273), with a soft X-ray count rate ∼50% that of Mrk 273. (For this paper, we assume $H_0 = 70$ km s^{-1} Mpc^{-1} and $q_o = \frac{1}{2}$.)

Recent spectroscopic observations of Mrk 273X have revealed that it is a Sy 2 galaxy itself, though at a much higher redshift (z=0.458) and with some very unusual properties (Xia *et al.* 1998a,b, 1999). Xia *et al.* (1999) report a soft X-ray luminosity (6.1×10^{43} erg s^{-1}) that is extraordinarily high compared to most Sy 2 galaxies even though the photon power law index has a typical Sy 2 value (-1.98). The radio luminosity ($L_{1.37\mathrm{Ghz}} \approx 1.0 \times 10^{40}$ erg s^{-1}) is also quite high for a Sy 2 (Yun & Hibbard 1999). Furthermore, the derived column density of neutral hydrogen (from the X-ray spectrum) is very low for a Sy 2: $\log(N_H) \approx 20.6$. Many Sy 2 galaxies have $\log(N_H) > 21$ (Turner *et al.* 1997), though values similar to Mrk 273X are not uncommon (Turner *et al.* 1998). High X-ray and radio power along with low N_H are more indicative of an unobscured view of the AGN (i.e., as in a Sy 1), and thus these observations challenge the conventional inclined dusty torus models for AGN. Xia *et al.* (1999) thereby contrast the possibilities that Mrk 273X may be either a Sy 2 or a narrow-line Sy 1 (NLS1) galaxy. They conclude that various optical emission line ratios and the X-ray spectral index weigh strongly against the NLS1 hypothesis and in favor of the Sy 2 interpretation. Xia *et al.* (1999) additionally discuss the evidence for X-ray variability in Mrk 273X, which is still not certain but nevertheless possible.

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Given the unusual properties of this faint galaxy, we were pleased to find it within the field-of-fiew of our HST image of Mrk 273 — part of our large HST survey of ULIRGs (Borne *et al.* 1997a,b, 1999a,b,c). We report here on our analysis of the Mrk 273X image and of its surrounding field (which includes many comparably faint galaxies). We describe the HST observations in §2 and the results of our image analysis in §3. The latter includes photometric and luminosity function derivations. We also summarize and discuss in §3 the properties of this galaxy in relation to the properties of analogous active galaxies.

2. HST IMAGING OBSERVATIONS

We obtained two sets of HST imaging observations of the primary ULIRG target, Mrk 273, as part of our large ULIRG Snapshot Survey program. In each set of observations, we used the WFPC2 camera to obtain two 400-sec images in the I-band (F814W filter). Pairs of images were used to remove the effects of cosmic-ray radiation events in the CCDs (assuming the events are uncorrelated and have no persistence from one image to the next). In one set of observations, Mrk 273 was centered in the WF3 CCD (with $0.10''$ per pixel), and in a second set, Mrk 273 was centered in the PC CCD ($0.046''$ per pixel). In the latter observations, we found the X-ray companion Mrk 273X in the WF4 CCD frame (Fig. 1). The standard calibrated data products were re-derived using the best calibration files and then were combined into a single cosmic-ray cleaned 800-sec image. Our analysis was carried out using this final cleaned image.

3. RESULTS OF IMAGE ANALYSIS

3.1. *Identification of Mrk 273X*

From their ROSAT PSPC X-ray images, Turner *et al.* (1993) give a boresight-corrected J2000 position for Mrk 273X at $13^h44^m47.9^s$, $+55^o54'11''$. Using this information and the images in Xia *et al.* (1998a, 1999), we have identified the optical counterpart in our WFPC2 image. We find the J2000 position (within the standard uncertainty of $\pm0.5''$ for HST positions) for Mrk 273X to be: $13^h44^m47.46^s$, $+55^o54'11.1''$. This is almost exactly the position given by Turner *et al.* (1993). We show in Figure 1 the $75''\times75''$ usable area of the WF4 CCD frame containing Mrk 273X. About 40 fainter galaxies are also seen in this frame. The darker grey shading of the background light distribution in the lower right quadrant (southwest) is real — this is the extended spray of emission from the tidal debris around Mrk 273, as indicated by Xia *et al.* (1998a, 1999). Mrk 273 is located in the PC frame just below the lower right quadrant of the WF4 frame shown here.

Mrk 273X is well resolved, with measurable light out to a radius of ∼50 pixels ($5.0'' \approx 25$ kpc). It is an essentially featureless galaxy, probably an elliptical or S0, with a small degree of flattening. It has a bright nucleus, typical of an elliptical galaxy.

3.2. *Photometric Properties of Mrk 273X*

We used various photometric tasks within IRAF and STSDAS to analyze Mrk 273X and its surrounding galaxies. The ELLIPSE task was used to analyze the surface brightness profile and shape of Mrk 273X. We find that the half-light radius for Mrk 273X is $0.40'' = 2.0$ kpc and the radially averaged ellipticity of the galaxy corresponds approximately to an E2 shape, at an average position angle of ∼115°. The derived intensity profile is shown in Figure 2. We find that the light follows the expected $r^{\frac{1}{4}}$ profile for an elliptical galaxy very well — over a range of 8 magnitudes in surface brightness. To determine how well the data are matched by the derived ELLIPSE model, we constructed a model galaxy using the derived parameters and subtracted that model from the data to produce a residual map. The different steps in this process are illustrated in Figure 3, including the original data (*upper left*), a 3×3-pixel boxcar-smoothed version of the data (*upper right*), the constructed model (*lower left*), and the residual (data minus model) image (*lower right*). From the near-zero residuals, we see that our "elliptical galaxy" model matches the data quite well.

According to Graham & Colless (1997), $R_{\rm eff} = 0.75R_{\frac{1}{2}}$ for a wide range of luminosity profile shapes and galaxy models. Assuming that this applies to Mrk 273X, we find $R_{\rm eff} = 0.30'' = 1.5$ kpc, which is small compared to most ellipticals (Scodeggio, Giovanelli, & Haynes 1998).

A very small companion galaxy is seen in the optical halo of the galaxy, approximately 16 pixels ($1.6'' \approx 8$ kpc) east of Mrk 273X's center (see upper panels in Fig. 3). In addition, three brighter companions are seen within $10''$ (≈ 50 kpc) of Mrk 273X, and possibly two additional fainter companions are also seen within that distance (south-southwest) of Mrk 273X), as shown in Figure 3. Note that the brightest of the companion galaxies have asymmetric and disk-like morphologies that are clearly evident at this spatial resolution ($0.2'' = 1$ kpc) and low S/N. Such features are not seen at all in Mrk 273X, which therefore clearly possesses an ellipsoidal early-type galaxy morphology.

The ELLIPSE model does show significant isophote twisting (ΔPA ≈ 30°) within the central $2''$ (∼10 kpc). This may be induced in Mrk 273X through interactions with the close companions. If the companions have that degree of influence on Mrk 273X, then their interaction may also be responsible for tidally triggering the AGN activity.

We used the IRAF APPHOT task to measure the I-band magnitude of Mrk 273X and of the surrounding galaxies (see §3.4). The NASA Extragalactic Database (NED) gives a magnitude of 19.6 (no passband specified, but probably R-band) for Mrk 273X. We find $m_I = 19.10$ (Cousins I) for the total light. For $z = 0.458$: $m - M = 41.66$ and therefore $M_I = -22.56$, which corresponds to the rest-wavelength V-band.

Xia *et al.* (1998a, 1999) report B=20.8 and R=19.6. Therefore, the colors of Mrk 273X are: $B - R$=1.2 and $B - I$=1.7. We compare these colors in Table 1 with those measured for the galaxies in the z=0.41 cluster Cl 0939+472 studied by Belloni & Roser (1996). The distance of that cluster is similar to that of Mrk 273X and so the K-correction can be ignored in the comparison of colors. We find that the $B-R$ and $B-I$ colors of Mrk 273X are consistent with the colors of the late-type Im and Scd cluster galaxies, both in the mean value and in the observed ranges of these colors.

3.3. *The Effect of an AGN*

Based on the color information (Table 1), we conclude that Mrk 273X is either a very late type galaxy (i.e., with recent star formation) or else its colors are seriously affected by the AGN (Sy 2 nucleus), or both. On-going star formation in Mrk 273X would suggest the presence of gas, which would provide a source of fuel for the AGN, and the nearby companions (Fig. 3) could provide a possible trigger for the activity.

As we see in Figure 2, the surface brightness of the galaxy follows the standard elliptical galaxy radial variation, providing no photometric evidence for an AGN point source contaminating the core brightness profile. However, the small measured value for the effective radius (1.5 kpc) may be an effect of the AGN contributing some fraction of the light in the core.

Mrk 273X has the optical spectral properties of a Sy 2 galaxy, but the radio flux, soft X-ray flux, optical morphology, and cluster dominance (§3.4) of a powerful radio galaxy (PRG). We compare and contrast various of these properties with the properties of analogous galaxies in Table 2. We see there that the properties of Mrk 273X span the range of the different types of active galaxies and yet do not correspond to any one AGN type. Its properties are atypical for Sy 2 galaxies in that Mrk 273X has very high L_{opt}, L_{radio}, L_{SX}, and $L_{H\alpha}$, but very low N_H (see §1). Its properties are most similar to IC 5063 — only L_{SX} differs significantly between the two sources. We know that IC 5063 has a very high column density ($\log N_H = 23.3$) and a high hard X-ray luminosity ($\log L_{HX} = 43.04$), as measured by Koyama *et al.* (1992). Thus the total (soft+hard) X-ray luminosity of the two sources is nearly the same (as are the optical, radio, and Hα luminosities). Mrk 273X is therefore a galaxy of the IC 5063-type, except that its low N_H allows a high flux of soft X-rays to escape. Inglis *et al.* (1993) found that IC 5063 shows broad lines in polarized light and thus likely contains an obscured PRG or Sy 1 nucleus (Morganti *et al.* 1998). Based on these comparisons, we believe that Mrk 273X is also a PRG.

3.4. *Luminosity Function of Surrounding Galaxies*

The brightest of the other galaxies seen in the WF4 frame are fainter than Mrk 273X, but they are all comparably bright. We have examined the full WFPC2 image (including the WF2 and WF3 frames) and we note that there are a couple of other small groupings of galaxies of similar brightness, number count, and spatial extent. However, those other groupings are relatively far from the WF4 frame (e.g., at the far edge of the adjacent WF3 frame and on the far half of the diagonally opposite WF2 frame) — at distances of 75″, 110″, and 130″ (where 100″ = 490 kpc). Even though they are not spatially close to the galaxies seen in WF4, these other groups could be associated with Mrk 273X nevertheless given that all of these galaxies have similar sizes and apparent magnitudes (i.e., at a similar redshift). To first order, given the observed spatial segregation of these groupings, we believe that the galaxies seen in WF4 comprise a small isolated group, of which Mrk 273X is the brightest member (at least, it is the brightest member that we have available within our WF4 image). Its rest-wavelength V absolute magnitude (§3.2) is consistent with this being a BCG (brightest cluster galaxy; Postman & Lauer 1995). The BCG status is further supported by the R magnitude (= 19.6), which makes Mrk 273X comparable in brightness to the brightest galaxies (ellipticals) in the z=0.41 cluster CL 0939+4713 that was studied with HST by Dressler *et al.* (1994a,b).

We used the IRAF APPHOT task to measure a metric I-band magnitude for the 34 circled galaxies in Figure 1. We measured the flux within a radius of 8 pixels (0.8″ = 4 kpc) and included only those galaxies with I-band metric magnitude brighter than 24.0. (Fainter galaxies could not be measured reliably in this short-exposure image.) Within our fixed metric aperture, Mrk 273X has I=19.5 (compared with I=19.1 for its total light). The spatial distribution of the marked galaxies in Figure 1 shows that Mrk 273X is far (∼200 kpc) from the center of the group. In fact, a bright dumbbell pair of galaxies is seen near the center, but the pair's combined *total light* has I=19.5. We show in Figure 4 the luminosity function for the 34 galaxies in our WF4 frame along with the I-band luminosity function for two clusters of galaxies at nearly the same redshift: cluster CL 0939+472 (z=0.41) from Belloni & Roser (1996), and cluster CL 2158+0351 (z=0.45) from Molinari *et al.* (1990).

A comparison of the histograms in Figure 4 reveals that the luminosity distribution of galaxies in the field surrounding Mrk 273X is similar to the bright end of a typical cluster luminosity function at that redshift. This further supports the notion that Mrk 273X is the brightest member of a poor cluster of galaxies at z=0.458. Given this galaxy's non-central location within the group, this is probably a dynamically young still-evolving cluster, perhaps still collapsing. In fact, this group may be on the verge of merging with the other small groups of galaxies seen in our wider WFPC2 field-of-view (see above). We note that there was no evidence in the X-ray images for an extended cluster-like hot ICM within this group.

4. SUMMARY

We have analyzed HST images of Mrk 273X, the serendipitously discovered X-ray companion to Mrk 273. Mrk 273X is at a much higher redshift and therefore not physically associated with Mrk 273 (Xia *et al.* 1999). Mrk 273X is a featureless early type galaxy and appears to be the brightest member of a small cluster of galaxies. The optical morphology of Mrk 273X (including its radial surface brightness profile) and its role as the dominant member of a cluster resemble the properties of a PRG: an elliptical or other early type galaxy. However, its colors and Sy 2 spectrum are typical of much later galaxy types. This suggests that the galaxy's colors are strongly contaminated by the AGN (through both its blue continuum and its emission lines). We believe that Mrk 273X is an active galaxy of the IC 5063 type, except that the soft X-ray source in Mrk 273X is not obscured as it is in IC 5063. Mrk 273X therefore appears to be a selectively obscured PRG in that the radio core and X-ray emitting region are exposed (as in a typical PRG or Sy 1), but the broad line-emitting region is obscured (as in a typical Sy 2). This may indicate that the obscuring torus has an intermediate line-of-sight inclination. Followup observations (particularly, redshift determinations) of the galaxies surrounding Mrk 273X would validate the cluster hypothesis and thus shed some light on the dynamical state of this system and possibly lead to an identification of the trigger (tidal companion) for the AGN activity.

Support for this work was provided by NASA through grant number GO-06346.01-95A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555. KB thanks Raytheon for providing financial support during his Sabbatical Leave. KB also thanks Ron Allen and the Space Telescope Science Institute for their hospitality in sponsoring his Sabbatical Visit. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has also made use of the on-line astronomical data services (`http://adc.gsfc.nasa.gov/`) at the Astronomical Data Center (ADC) at NASA Goddard Space Flight Center.

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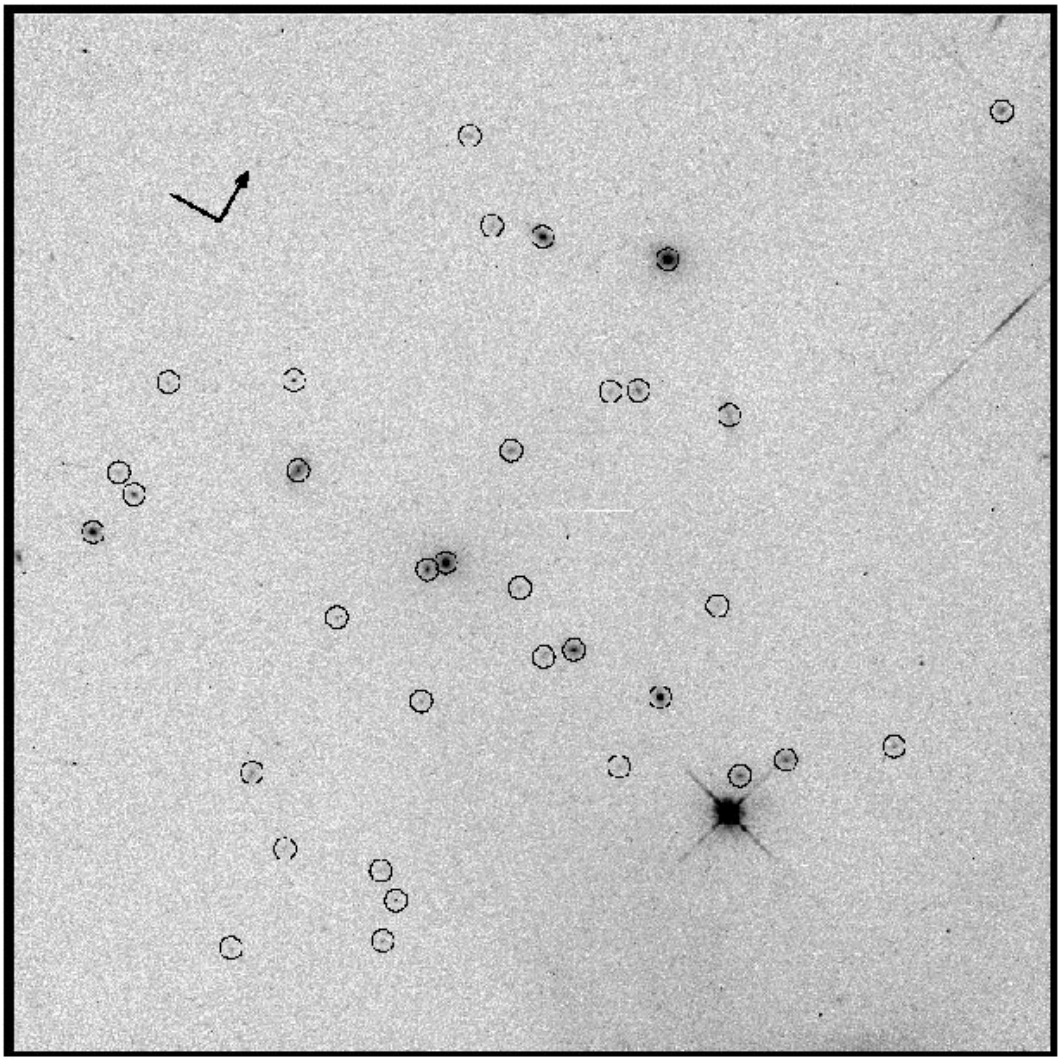

FIG. 1.— 75″×75″ section of HST WFPC2 image, showing the usable portion of the WF4 CCD frame. At the redshift of Mrk 273X (z=0.458), 75″ corresponds to 370 kpc. The arrow on the North-East indicator points north. All of the galaxies whose estimated I magnitude is brighter than 24.0 are circled. These are used to produce the luminosity function shown in the top panel of Fig. 4 — the magnitudes represented in Fig. 4 were measured within a circular aperture of radius 0.8″ (= 8 pixels), corresponding to the circles around each marked galaxy in this image. The brightest galaxy in the frame is Mrk 273X — it is the brightest object in the upper right quadrant of the image. The dumbbell galaxy pair just to the left of center has a combined I magnitude of 19.5, still fainter than the m_I=19.1 for Mrk 273X. There are 34 galaxies marked with $m_I < 24.0$. At the redshift of Mrk 273X, $m - M = 41.66$, so that the faintest galaxy marked has $M_I \approx -17.7$ (if it is at the same distance as Mrk 273X).

TABLE 1
COLORS OF MRK 273X VS. CLUSTER GALAXIES AT z=0.41 (BELLONI & ROSER 1996)

Galaxy Type	Number	$< B-R >$	Range of $B-R$	$< B-I >$	Range of $B-I$
E	139	2.4	1.6–3.0	3.5	2.5–4.4
E+A	42	2.0	1.4–2.5	3.0	2.3–3.7
Sbc	32	1.7	1.3–2.1	2.6	2.0–3.2
Scd	16	1.4	0.8–2.4	2.2	1.7–3.4
Im	17	1.1	0.9–1.4	1.7	1.5–2.0
Mrk 273X	...	$B-R=1.2$		$B-I=1.7$	

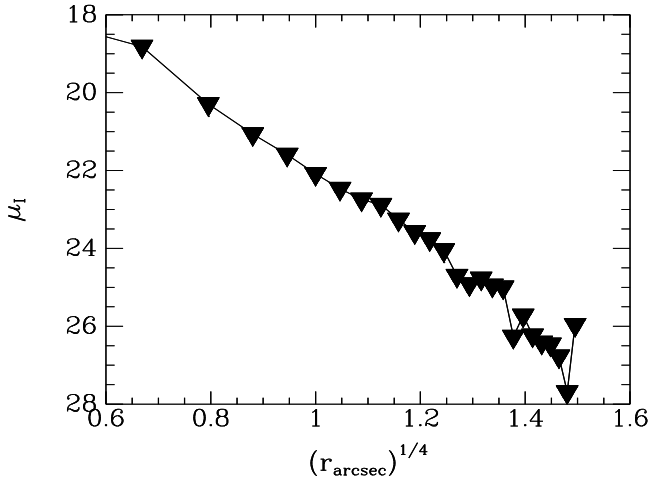

FIG. 2.— Derived intensity profile for Mrk 273X from the IRAF/STSDAS ELLIPSE task. The intensity scale is in units of I magnitude per square arcsec, and the radial scale is in (arcsec)$^{\frac{1}{4}}$ units. Note that the profile follows nearly a straight line (de Vaucouleurs profile), as would a typical elliptical galaxy. A very tiny (almost imperceptable) rise in the curve at $r^{1/4} \approx 1.12$ may be caused by the very small companion seen embedded in the optical halo of Mrk 273X (Fig. 3, at 1.6″ east). We did not mask out that companion in our ELLIPSE fit due to its very low brightness — we see here that the effect of including it is minimal.

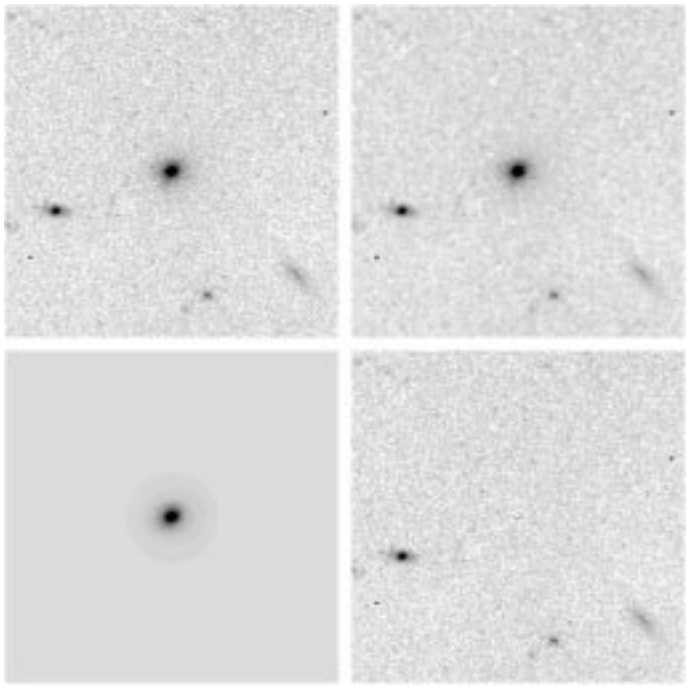

FIG. 3.— *Upper left*: 25″×25″ section of the HST WFPC2 image, centered on Mrk 273X (where 25″ corresponds to 125 kpc). At least three (and maybe as many as five) companion galaxies are seen within ∼10″ (≈ 50 kpc). North is up and east is to the left. Note the smooth elliptical appearance of Mrk 273X, with no evidence for a disk or flattened component. *Upper right*: 3×3-pixel boxcar-smoothed version of HST image. *Lower left*: IRAF/STSDAS ELLIPSE model for Mrk 273X (fit out to radius = 5″). The mean ellipticity of the model (out to radius = 1″) is 0.17, and the mean isophotal position angle is 115°. The half-light radius is 0.4″ (= 2.0 kpc). *Lower right*: Residual HST image, produced by subtracting the model (*lower left*) for Mrk 273X from the upper left image. Note the near perfect subtraction of the Mrk 273X galaxy image (except at the very center), indicating the very good approximation of the ELLIPSE-fit model to the actual data.

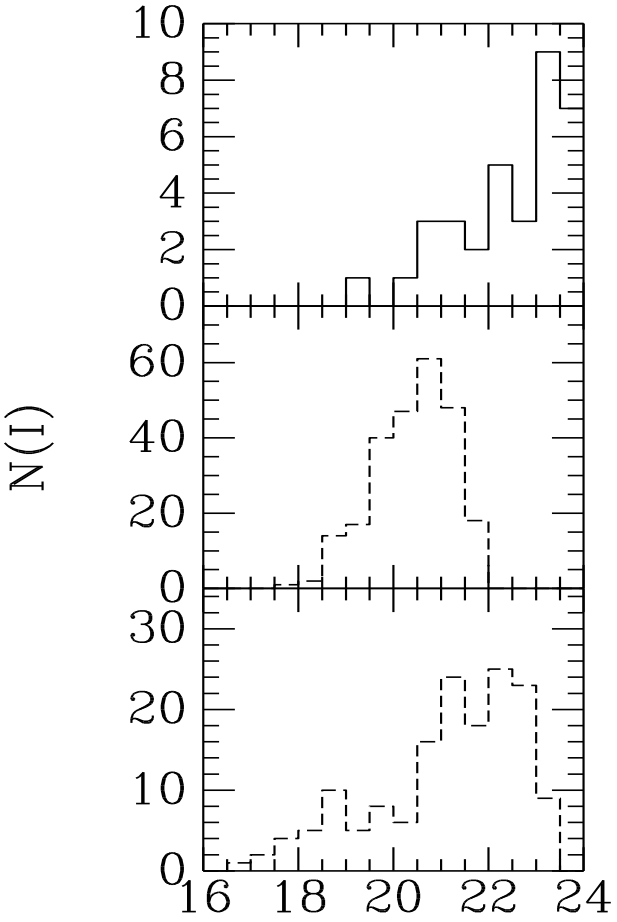

FIG. 4.— Luminosity function for 3 regions. Each histogram shows the number distribution of galaxies as a function of I magnitude (Gunn i for the bottom plot). Top: field around Mrk 273X (z=0.458; this paper). Middle: cluster CL 0939+472 (z=0.41; Belloni & Roser 1996). Bottom: cluster CL 2158+0351 (z=0.45; Molinari *et al.* 1990). The galaxies measured for the Mrk 273X distribution (top panel) are those that are indicated in Fig. 1. Both Belloni & Roser (1996) and Molinari *et al.* (1990) had magnitude cutoffs in their samples: $R = 22.5$ and Gunn $r = 23.5$, respectively.

TABLE 2
PROPERTIES OF MRK 273X AND COMPARISON ACTIVE GALAXIES

Galaxy	Type	z	Distance (Mpc)	I (mag)	M_I (mag)	$\log(L_X^{\rm soft})$ (erg/s)	$\log(L_{\rm radio}^{1.4\rm GHz})$ (erg/s)	$\log(L_{H\alpha})$ (erg/s)
NGC 5506	Sy 2	0.00618	26.5	13.12[a]	-18.9	41.98[b]	38.57[c]	40.51[d]
NGC 2992	Sy 2	0.00771	33.0	12.42[a]	-20.1	42.33[b]	38.52[e]	40.90[f]
IC 5063	Sy 2 / RG	0.01135	48.7	10.64[g]	-22.8	<41.40[b,h]	39.60[i]	41.23[j]
Fairall 9	Sy 1	0.04702	204	13.16[a]	-23.3	44.10[k]	?	43.48[l]
3C 273	QSO	0.15834	703	12.17[a]	-27.1	45.8[m]	43.62[c]	44.81[l]
Mrk 273X	Sy 2	0.458	2150	19.10[n]	-22.6	43.8[o]	40.0[p]	41.58[q]

[a]Kotilainen et al. (1993)

[b]Fabbiano et al. (1992)

[c]White & Becker (1992)

[d]Storchi-Bergman et al. (1995)

[e]Ulvestad & Wilson (1984)

[f]Forbes & Ward (1993)

[g]Estimated from $V - I = 1.23$ (Buta & Williams 1995) and $V = 11.87$ (RC3)

[h]Koyama et al. (1992) measured $\log N_H = 23.3$ and the hard X-ray flux, yielding $\log L_{HX} = 43.04$

[i]Morganti et al. (1998)

[j]Colina et al. (1991)

[k]Ceballos & Barcons (1996)

[l]Steiner (1981)

[m]Brinkmann et al. (1994)

[n]This paper

[o]Turner et al. (1993)

[p]Yun & Hibbard (1999)

[q]Xia et al. (1999)